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Shape Visualization Method of Flexible Colonoscopy Using non Visual Sensor Network for Monitoring of Operation

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Abstract—3D Visualization method of shape of flexible colonoscopy in simulated computing environment is proposed. Signals from sensor network are used to calculate the orientation of the body of each sensor. Position of each sensor is estimated from the orientation using assumption of forward kinematics in robotics. This data are then interpolated with curve fitting method to give natural impression of shape to surgeon who are watching monitor. The resulting simulated curve shows that motion of shape of colonoscopy can be simulated at it is.

Keyword- Visualization, Non visual sensor network, forward kinematics, shape

I. INTRODUCTION

Surgeons in operation of colonoscopy rely on the intuition on the shape information of colonoscopy while manipulating during operation. This intuition is usually formed through training with long time manipulation in the empirical site. Wrong manipulation while operating might make damage on patient, and the mistake of the manipulation by surgeon has been reported as the cause of about 2% of medical trouble per annual year [1],[10].

In this aspect, the visualization method to assist surgeon was needed. But the difficulty in visualization is that image from the camera cannot be used to look for the shape. At the present, the commercial visualization system which uses non visual sensors [5] was developed and is used when necessary [1][9][11].

In this paper, the new visualization method is proposed to support surgeon's determination while operating colonoscopy. This method consists of several parts. Position or length estimation with non visual sensors is researched widely in a variety of filed such as human motion capture [6],[7]. Frenet-Serret based description is also researched[8].

In order to fit smoothly with experimental data, condition of monotonicity was studied for piecewise cubic interpolation [2],[3]. Smoothness and monotonicity are important concept in interpolation technique. Minimized bending energy technique is also used to find monotonic and smooth interpolant[4]. This concept was useful to extract smooth and conformal surface interpolation in medical imaging area.

This paper proposes method in section II. In section III experiment and results are shown and section IV discusses its merit and demerit.

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II. VISUALIZATION METHOD

A. Skeletonized shape evaluation based on orientation

Let's suppose that the colonoscopy body is composed of several joint link pair as in Fig.1. Each joint is assumed to have 3 degree of freedom in rotation. The orientation sensors are fixed at the center of the link. The length of each link is known as a prior knowledge. Then we can think that when colonoscopy moves, each joint will have their own trajectory at its joints.

Transformation matrix based on the roll, pitch and yaw angle is obtained as follows. Firstly, we rotate the coordinate frame of the sensor body from the initial orientation by the amount of the difference of successively measured roll, pitch and heading angle as (1).

$$R_{\phi,\theta,\varphi} = R(\varphi)R(\theta)R(\phi) = \begin{bmatrix} C\varphi C\theta & C\varphi S\theta S\phi - S\varphi S\phi & C\varphi S\theta C\phi + S\varphi S\phi \\ S\varphi C\theta & S\varphi S\theta S\phi + C\varphi C\phi & S\varphi S\theta C\phi - C\varphi S\phi \\ -S\theta & C\theta S\phi & C\varphi C\phi \end{bmatrix} \quad (1)$$

where S, C means sine and cosine function each.

The transformation matrix reflecting the orientation of each link can be described as (2).

$$T = \begin{bmatrix} R_{\phi,\theta,\varphi} & d \\ 0 & 1 \end{bmatrix} \quad (2)$$

The translation component d of transformation matrix is zero as there is no movement of each link vector.

Then, the transformation matrix from the first link to the i^{th} link can be written as (3).

$${}^0T_i = {}^0T_1 \cdot {}^1T_2 \cdots {}^{i-1}T_i = \prod_{k=1}^{i} T_i \quad (3)$$

The initial posture of the manipulator is assumed to have a specified configuration as in Fig.1. The initial configuration is known as a priori knowledge. The length of link and its relative angle between previous and current links are also known and measured with time.

In this case, the position of current link vector can be written by the product of the transformation matrix and previous link vector.

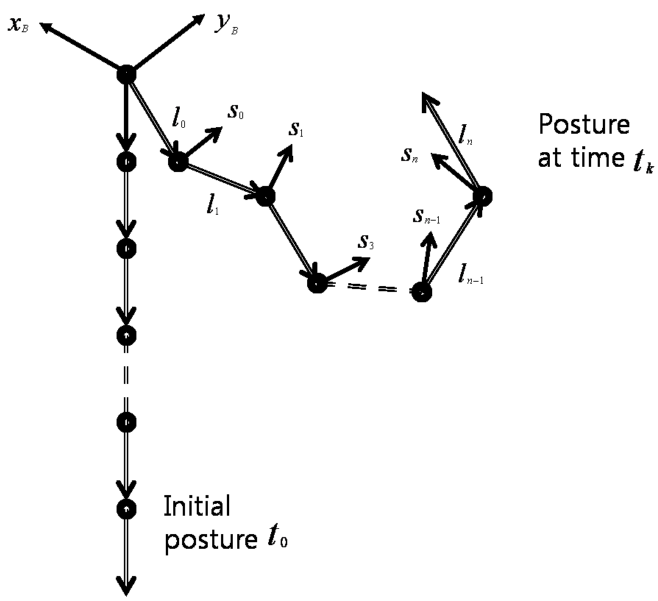

Fig. 1 colonoscopy is approximated as collection of a lot of joint link pair. $l_0, l_1, \cdots l_n$ are link vectors, $s_0, s_1, \cdots, s_n$ are orientation vectors of links, which are measured as a form of roll, pitch and yaw angle measured by the sensors on the links.

$$l_i = {}^0T_i \cdot l_{i-1} \tag{4}$$

where i is the sequence number of the link from the base to the distal tip of endoscope and k is the time step.

Finally, the position vector p_n of nth joint can be described as follows.

$$\begin{aligned} p_n &= l_0 + l_1 + \cdots + l_i + \cdots + l_n \\ &= l_0 + {}^0T_1(l_1) + {}^0T_2 \cdot l_2 + \cdots + {}^0T_i \cdot l_i + \cdots + {}^0T_n l_n \end{aligned} \tag{5}$$

We assumed that the colonoscopy can be represented as consecutive joint link pair as in Fig.1. The skeletonized shape of colonoscopy can be seen as a line which passes through the longitudinal axis of colonoscopy. The shape is then described as the collection of position of every link vector.

$$\Omega = \{p(i) | i = 1, 2, \cdots, n\} \tag{6}$$

where Ω is the shape $p(i)$ is the points of link vector and n is the number of link vectors.

B. Consideration on the Flexibility of Colonoscopy

The next problem is how flexible property of colonoscopy can be reflected to (6). (6) has limited discrete points as the number of sensor in the network is limited. In reality, the length of link should be so small enough to ensure the flexibility of the colonoscopy.

According to the manual, the shape of colonoscopy should not make steep bending while operating. In mathematical meaning, this means that the smoothness and curvature constraint below should be accomplished at the endpoints of each interval between key points.

Smoothness constraint

The endpoints of interval which are made of key points should be smooth.

$$\Omega_i' = \Omega_{i+1}' \tag{7}$$

where $i = 1, \cdots, n$ is the number of interval.

Curvature constraint

Colonoscopy should not be treated within specified curvature.

$$\kappa \le \delta \tag{8}$$

where the κ is the curvature of curve, δ is allowed value for curvature.

Curvature constraint means that the order of polynomial in curve fitting should not be higher order than the specified order such that entire curve makes only one circle in the entire length. If we define the bending energy as the energy that is stored in the curve by bending with specified curvature, evaluating curve can be thought to find a curve satisfying the constraint of curvature $\kappa(\tau)$ which minimizes the bending energy [3].

$$E_b(\tau) = \int_{\tau_0}^{\tau_f} \|\kappa(\tau)\|^2 d\tau \tag{9}$$

Cubic Spline interpolation satisfies the above constraints well. Spline interpolation uses key points as endpoints and divides curve into several intervals. 3rd order polynomial is implemented as interpolant between interval.

The expression for $E_b(\tau)$ may be written in terms of the first derivatives as follows [3].

$$E_b(\tau) = \sum_{k=0}^{n-2} \int_{\tau=\tau_k}^{\tau_{k+1}} \Omega_k''(\tau) d\tau \tag{10}$$

$$= \sum_{k=0}^{n-2} \int_{\tau=\tau_k}^{\tau_{k+1}} \frac{1}{\Delta\tau_k^2} \left[H_0'' h \Omega_k + H_1'' h \Omega_{k+1} + \Delta\tau H_2'' h \Omega_k' + \Delta\tau H_3'' h \Omega_{k+1}' \right]^2 d\tau$$

where $h = \dfrac{\tau - \tau_k}{\Delta\tau_k}$

$$H_0'' = 12\tau - 6$$
$$H_1'' = -12\tau + 6$$
$$H_2'' = 6\tau - 4$$
$$H_3'' = 6\tau - 2$$

From $\frac{dE_b(\tau)}{d\tau} = 0$, optimized solution for the spline curve is obtained. On each interval, cubic spline which minimize (10) with condition of (7), (8) is obtained. Specifically, natural cubic spline is possible if the end condition of start point and end point of entire curve are free.

C. Parametric trajectory with time

Finally, the trajectory of the curve which colonoscopy makes with time is evaluated. This is time varying version of (6). The panoramic trajectory Γ of the moving shape with time can then be described as follows.

$$\Gamma = \{\Omega(t_k) | t_k = t_s, \cdots, t_f\} \tag{11}$$

where t_k is the time step t_s, t_f are the start ,end time step of the simulation.

III. EXPERIMENTS AND RESULTS

A. Experiment Procedure

B.1 Orientation evaluation from accelerometer and magnetometer signals

6 sets of sensor unit were installed on the test body. 18 channels of accelerometer signals and another 18 channels of magnetometer signals were processed with digital filter to obtain the resulting orientation of each sensor bodies based on the fixed frame as in Fig.2. The gyro is not used as operation is mainly in the quasi static state

B.2 Accuracy Test Procedure

(1) Self accuracy test

Sine curve was used to check the self accuracy of the method. The link segment was fixed at 1.37 which came from 1/6 of total length of sine curve. The points on which sensors are assumed to put were calculated along the sine curve. The averaged value of both end of line segment was used as the orientation of the line segment.

(2) Effect of number of sensor to the accuracy.

In order to look for relation between the accuracy and the number of sensor in the network, we used circle as a standard shape because circle curve is the standard geometry with curvature which can be measured easily.

The percentage ratio of (1 - measured data / its simulated data) was used as metric of error. Test was made, decreasing the number of sensors to 6, 5 and 4 sets in the network. Then, percentage of measured data on the basis of simulated data was calculated.

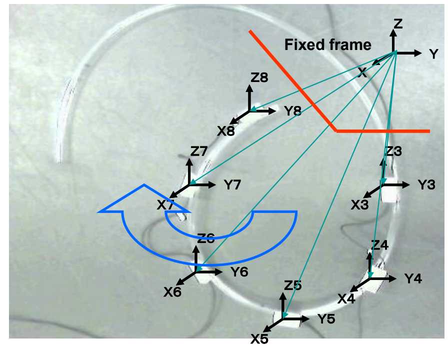

Fig.2 sensors are attached on the body of flexible tube. Tube dia. 9mm, length 120mm. Sensors are in the white plastic boxes.

B.3 Visualization Test Method

The time trace of shape of the colonoscopy was calculated while acquiring data from the sensor network using (11). Calculation time was about 150ms per frame with Pentium 4 dual core Intel processor. In this test, entire data was acquired with offline for validation of method.

IV. DISCUSSION

A. Accuracy Test

A.1 Comparison between True and Simulated Curves

Fig.3 shows the comparison between the true curve and the simulated curve. The angle of pitch in the 3 kind of orientation angles was used for demonstration.

The angle of simulated one is slightly different compared to the ground truth. The discrepancy of position of each data points comes from angle difference between ground truth and simulated one. We have regarded the link as rigid body. So the orientation is assumed not to be changed in one link segment.

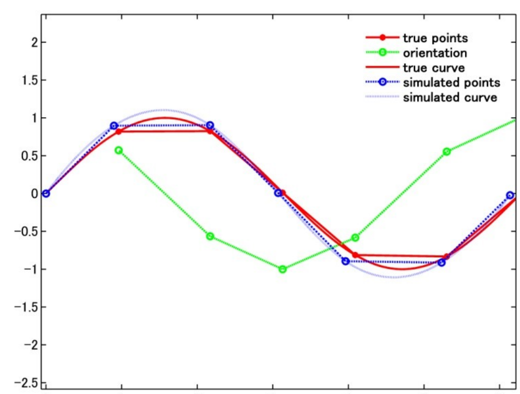

Fig.3 comparison between the true curve and the evaluated curve. Blue lines are true sine curve and points.

A.2 Accuracy Change according to the Number of Sensor.

Fig.4 shows how much the error comes between measured and simulated result. As we can guess generally, Fig.4 shows that the error of length of linkage is reduced as the number of sensor in the network is decreased.

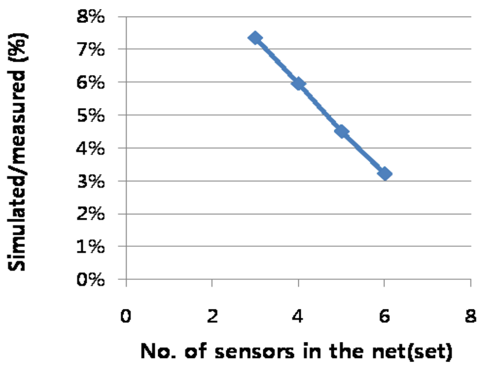

Fig.4 Simulated results are compared with measured ones. As number of sensor in the network is reduced, the percentage error of (1- S/M) is also reduced.

B. Panoramic display for surgeon assistance

The trajectory of the curve is evaluated with time step. In Fig.5 the green circles display the key points which were estimated by the measured sensor data.

There are some noisy movements on the boundary of shape. Blue trajectories are data and green trajectories are wrong trajectory contaminated by the noises which are shown in Fig. 5.

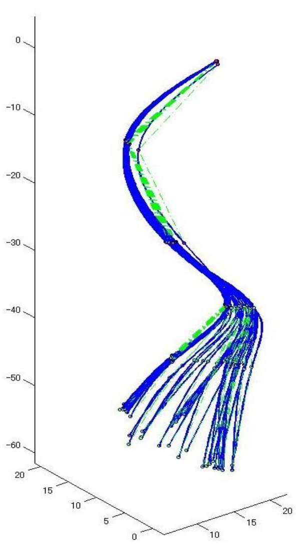

Fig.5 Trajectory of colonoscopy with time. Blue circle and red circle displays the sensor locations

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